EXPONENTIAL ANISOTROPY OF SOLAR COSMIC RAYS

J. W. Bieber, P. A. Evenson, and M. A. Pomerantz
Bartol Research Foundation of The Franklin Institute
University of Delaware, Newark, Delaware 19716

ABSTRACT

On 16 February 1984 a flare on the sun's invisible disk produced a large, highly anisotropic solar particle event. A novel technique, in which interplanetary scattering parameters are determined purely from the form of the particle anisotropy, is here applied to energetic particle data from neutron monitors and the ICE spacecraft.

1. Introduction. Recent theoretical investigations (Roelof, 1969; Kunstmann, 1979; Earl, 1981) indicate that the cosmic ray anisotropy may appropriately be expressed as an exponential function of pitch angle:

$$f = c_0 + c_1 B \exp\left\{\frac{(4-q)}{3}\frac{\lambda}{L}\,\mu|\mu|^{1-q}\right\} . \tag{1}$$

Here, f is the phase space density, c_0 and c_1 are constants, μ is the cosine of pitch angle, B is the magnetic field magnitude, λ is the scattering mean free path, L is the magnetic field scale length, and q is a parameter which, according to quasilinear theory (Jokipii, 1971), is related to the slope of the power spectrum of magnetic field fluctuations. Provided that q and the ratio λ/L do not change with distance, (1) is an exact solution of the steady-state Boltzmann equation in arbitrary guiding field configurations, including the Parker field. Solar particle anisotropies are, of course, not precisely steady-state. Nonetheless, it might reasonably be expected that (1) constitutes a better approximation to actual anisotropies than the often utilized first-order anisotropy ($f = c_0' + c_1'\mu$) which is a solution of neither the steady-state nor the time-dependent Boltzmann equation.

On 16 February 1984, a flare on the invisible disk of the sun produced an unusual solar particle event that was recorded by neutron monitors on Earth (Pomerantz et al., 1984) and by the MEH instrument aboard ICE, which at that time was located on nearly the same nominal Parker field line as Earth at a distance of 0.07 AU upstream. The best timing of the parent flare is given by the sudden onset of radio emission at 0858 UT (Earth-received time) from beyond the western limb of the sun. This highly anisotropic event provides an ideal observational basis for testing which of the alternate forms of pitch angle distribution -- first-order or exponential -- best describes energetic solar particle anisotropies.

2. Neutron Monitor Observations. To determine the form of solar particle anisotropy in this event, the fractional increases recorded by 8 polar neutron monitors during the interval 0900-1000 UT were corrected to sea level pressure. An effective value of μ was calculated for each station. The data were then fitted to a first-order anisotropy and to the exponential anisotropy (1) with the parameter q set equal to unity. Separate determination of q from the available neutron monitor data was not feasible for this event.

Results of this analysis appear in Figure 1. It is immediately apparent that the exponential anisotropy provides a substantially better description of the data than the first-order anisotropy. The goodness-of-fit parameter, χ^2, is nearly 10 times larger for the first-order fit than for the exponential fit. Even this poor fit for the first-order case is accomplished only by resort to the unphysical artifice of assuming negative densities for μ less than -0.4. Changes in μ appear between the two fits because the best-fit symmetry axis differs slightly for the two assumptions.

The value of λ/L corresponding to the exponential plotted in Figure 1 is 2.8. However, comparable agreement was obtained for λ/L in the range 2-10. The value of L at this time, as calculated for a Parker magnetic field corresponding to the ICE-observed solar wind speed of 280 km/s, was 1.4 AU. Hence, at neutron monitor energies (> 400 MeV) the scattering mean free path in this event was 3 AU or larger.

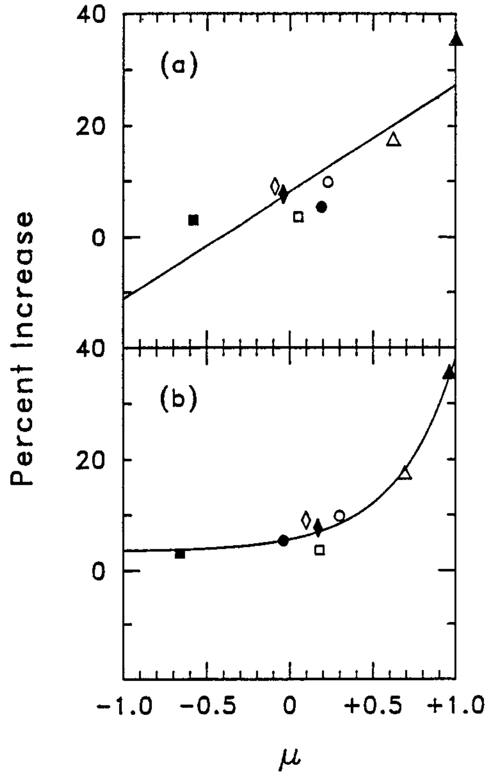

Fig. 1. Two alternate forms of pitch angle distribution are fitted to hourly-averaged neutron monitor data from Thule (○), McMurdo (●), Alert (□), Inuvik (■), Goose Bay (▲), Mawson (△), Apatity (⧫), Oulu (◊).

3. Spacecraft Observations. Measurements of the flux of protons with energies 35-145 MeV from eight equally spaced arrival directions are made every 97 seconds by the MEH instrument on the ICE (formerly ISEE-3) spacecraft (Meyer and Evenson 1978). Since the magnetic field is also measured at the spacecraft (E. Smith, private communication via ISEE common datapool tape), a representative pitch angle for each viewing direction can be computed directly by averaging the magnetic field observations over the period of the particle flux measurement. This is in contrast to the neutron monitor analysis wherein the direction of the field was a free parameter. Figure 2 shows the 35-145 MeV ICE data (10 minute average) at approximately 0955 UT on 16 February 1984, near the maximum of the event at these energies. The

sectored data obviously do not follow a straight line (first-order anisotropy) but the exponential (1), with a choice of q=1.2 and λ/L=2.8, provides an excellent fit, as shown by the plotted curve.

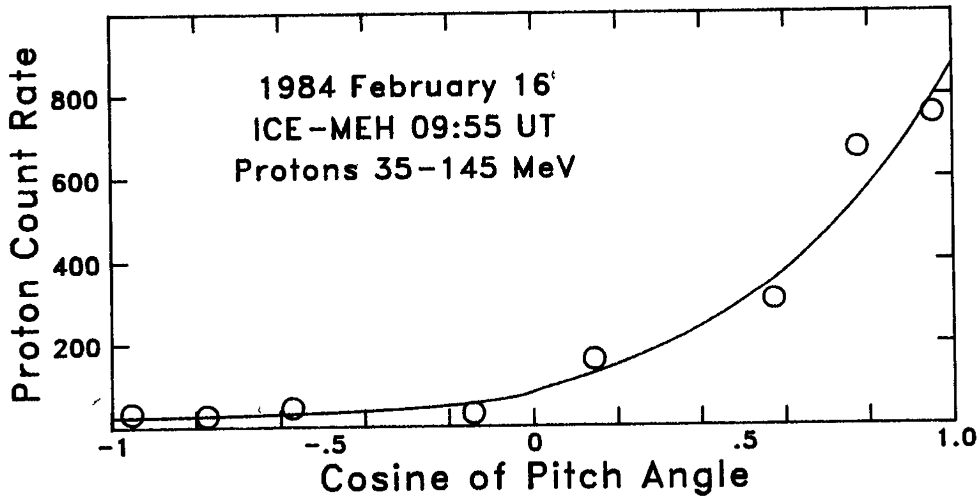

Fig. 2. Sectored ICE particle data (circles) are compared to an exponential anisotropy (curve) with λ/L = 2.8 and q = 1.2.

The persistent high anisotropy of the event and the long mean free path determined from the shape of the pitch angle distribution suggest that the entire time profile is a reflection of continued injection at or near the sun. We have modeled the time profile using coronal diffusion (Reid, 1964) and interplanetary focused diffusion (Bieber et al., 1980) and find excellent agreement. A key result of this analysis is that the flow at the position of the spacecraft is at all times approximately steady state. Changes with time are nearly all due to changes in the source strength at the sun.

Such a steady state flow may be used to look for changes in the scattering parameters which determine the shape of the pitch angle distribution. A related analysis conducted by Bieber and Pomerantz (1985) uses long term averages of neutron monitor data. The shape of the pitch angle distribution may be characterized many ways, one of which is to consider ratios of the amplitudes of harmonic components determined by Fourier analysis of the counting rate as a function of arrival direction. Figure 3 shows the average flux, ratio of second to first harmonic r_2/r_1, and ratio of third to first harmonic r_3/r_1 as a function of time. Note the distinctly different values of the harmonic ratios before and after the data gap. This jump implies a reduction in the mean free path for scattering by almost a factor of two, while q remains nearly unchanged. It is likely that this change is related to the change in the properties of the solar wind which is indicated by the increase in the magnetic field magnitude also shown in Figure 3.

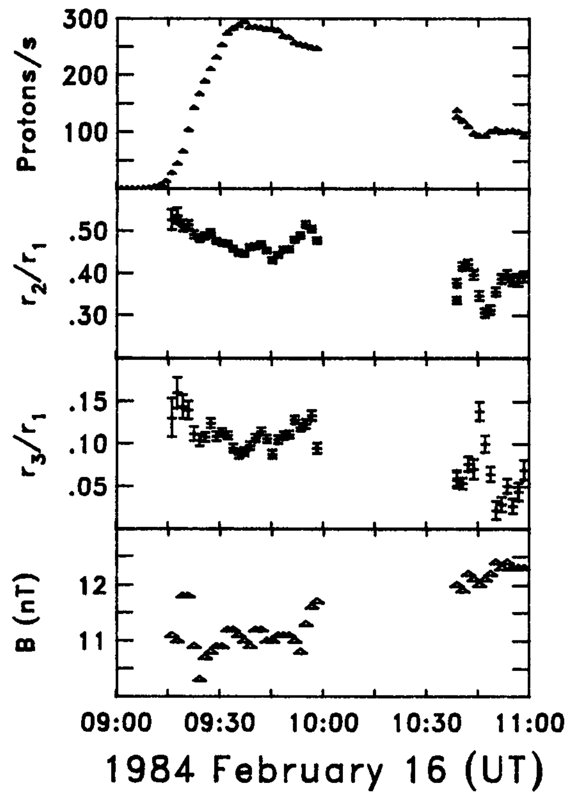

Fig. 3. Time profiles of average particle flux, harmonic ratios r_2/r_1 and r_3/r_1 (see text), and magnetic field B observed at ICE.

4. Conclusions. Local measurements of important parameters of interplanetary particle propagation can be made with high time resolution if particle anisotropies can be measured with sufficient statistical accuracy. Analysis of energetic particle data for the event of 16 February 1984 from neutron monitors and from ICE leads to the following conclusions: (1) Particle anisotropies are better described by an exponential function of pitch angle than by the commonly assumed first-order anisotropy. (2) Fitting to the exponential anisotropy allows both the scattering mean free path λ and the parameter q, which characterizes the dependence of the scattering rate upon pitch angle, to be determined. For this event, it is found that λ is greater than 3 AU and q is approximately 1.2. (3) An apparent change in the scattering mean free path occurred in connection with a small change in the magnitude of the interplanetary magnetic field.

5. Acknowledgments. This research was supported by the National Science Foundation under grants ATM-8303758 and DPP-8300544 and by NASA under grant NAG-5-374.

References

Bieber, J. W., and M. A. Pomerantz, (1985), paper SH 4.5-21, this conference.
Bieber, J. W. et al., (1980), J. Geophys. Res., 85, 2313.
Earl, J. A., (1981), Astrophys. J., 251, 739-755.
Jokipii, J. R., (1971), Rev. Geophys. Space Phys, 9, 27-87.
Kunstmann, J. E., (1979), Astrophys. J., 229, 812-820.
Meyer, P. and P. Evenson, (1978), IEEE Trans. Geosci. Electronics, GE-16, 180.
Pomerantz, M. A. et al., (1984), Proc. Intl. Symp. on C-R Modulation in the Heliosphere, pp. 437-443, Morioka, Japan.
Reid, G. C., (1964), J. Geophys. Res., 69, 2659.
Roelof, E. C., (1969), Lectures in High-Energy Astrophysics, NASA Spec. Publ. 199, pp. 111-135, NASA, Washington, D. C.